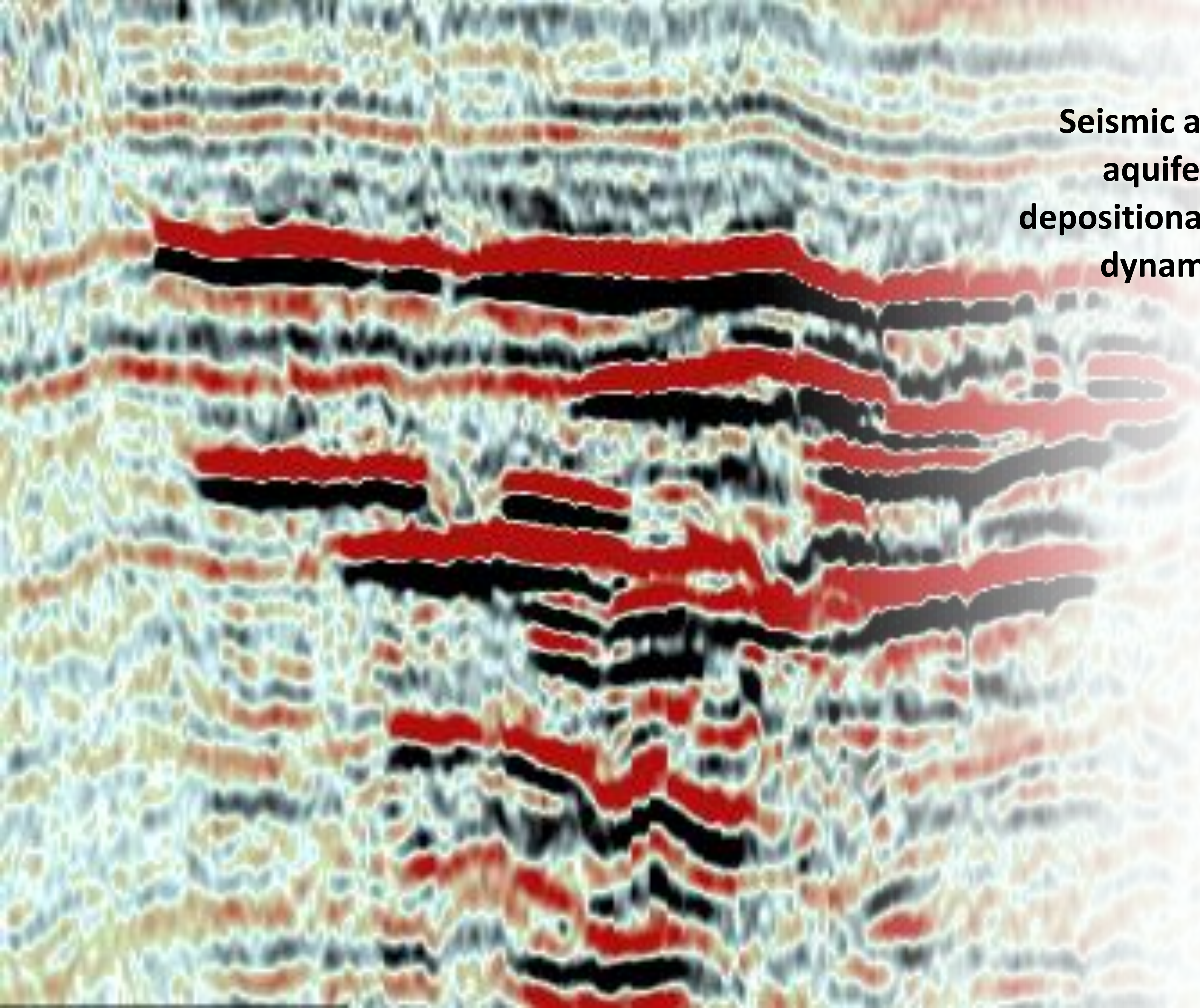

Seismic analysis of the Sleipner CO2 saline aquifer storage to characterize facies depositional architecture, plume anatomy, flow dynamics, and pressure perturbation

Geovani C. Kaeng

Mateusz Zareba, PhD*

Ilia Terentiev

HALLIBURTON

SPE International
Aberdeen Section

May 1st – 2nd, 2024

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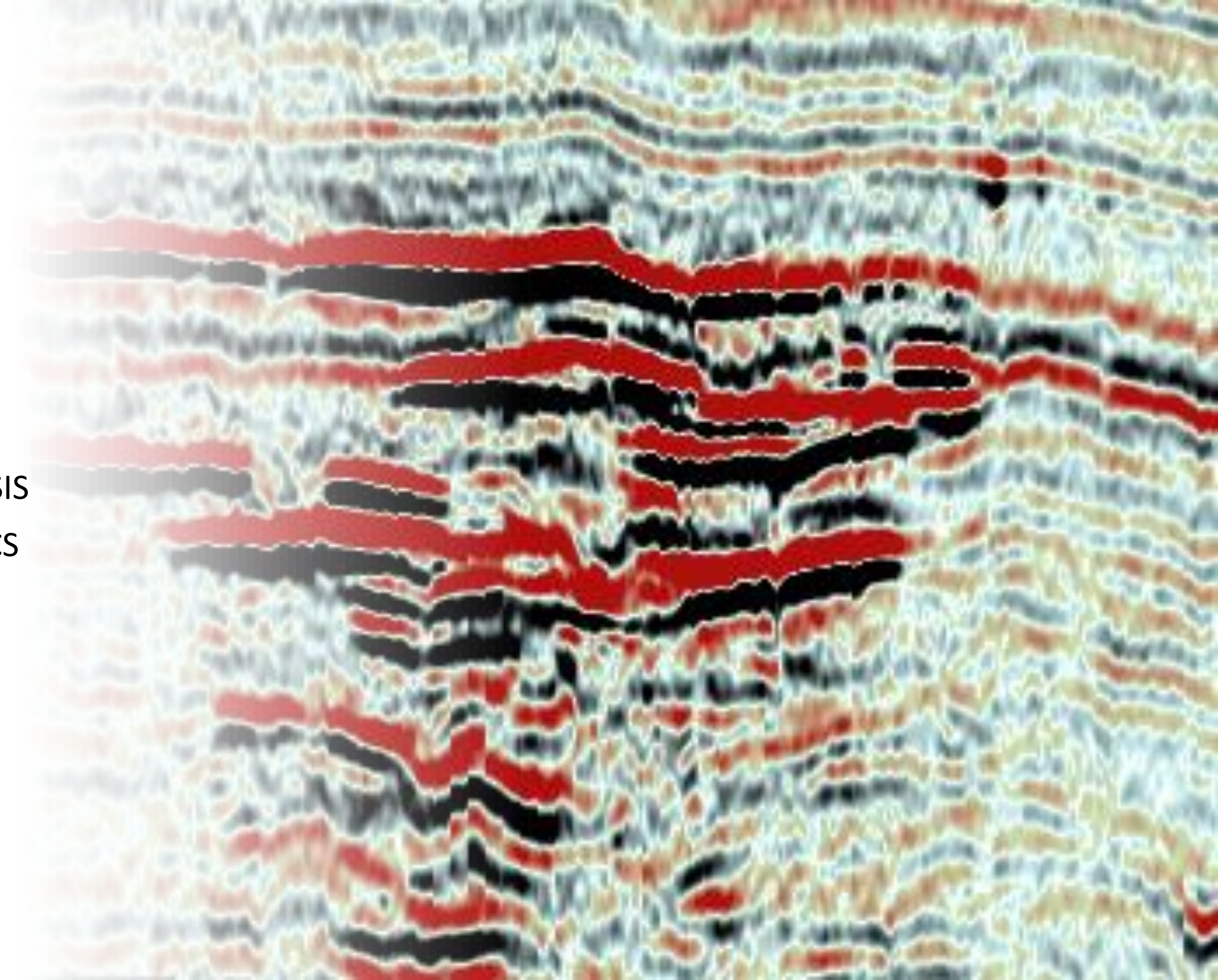
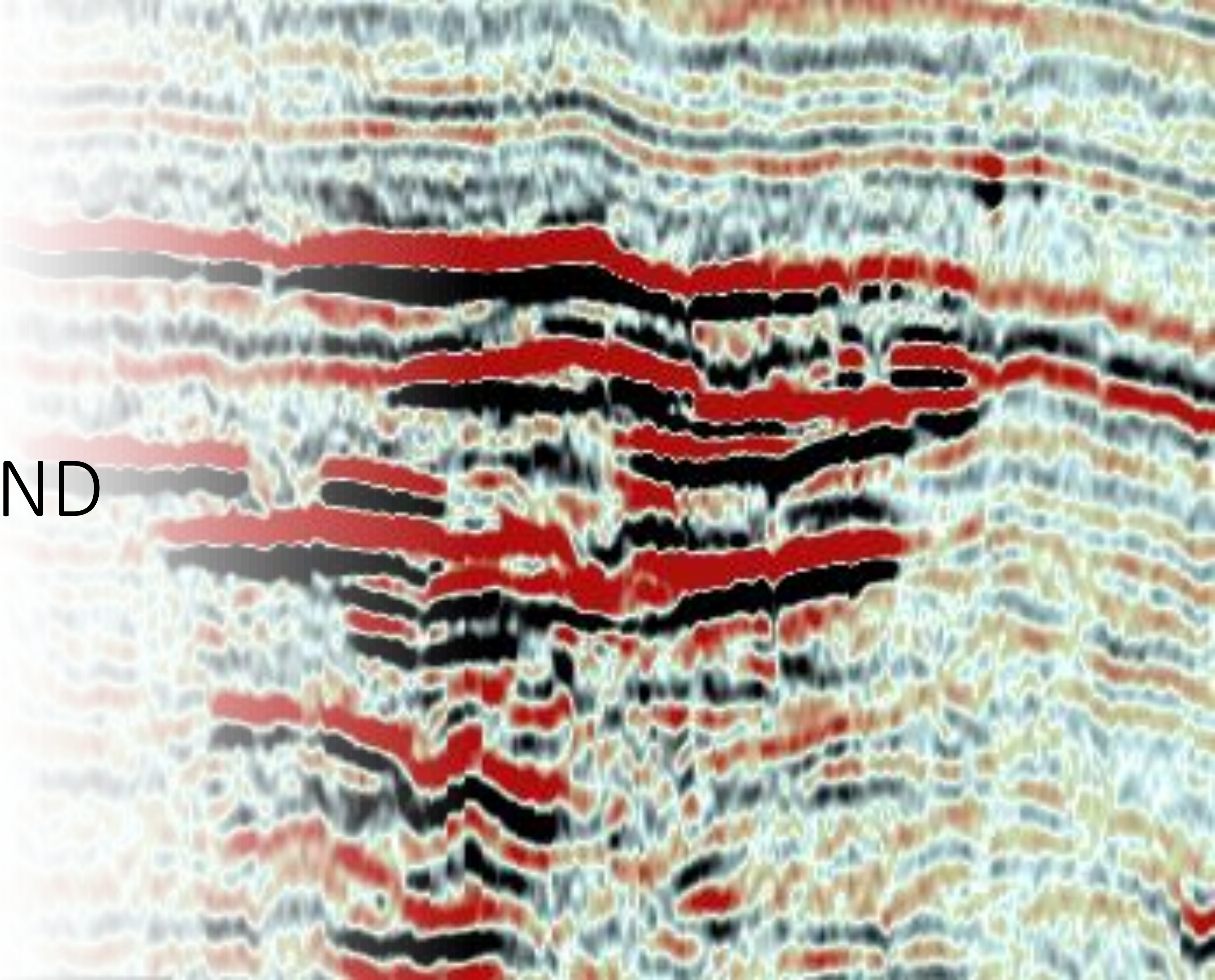
Content

- BACKGROUND
- SEISMIC PLUME ANALYSIS
- PLUME FLOW DYNAMICS
- SUMMARY & ACKNOLEDGEMENT

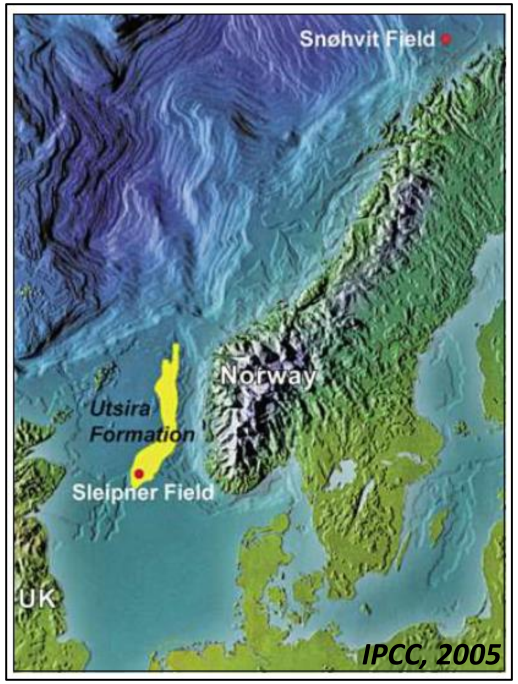


BACKGROUND

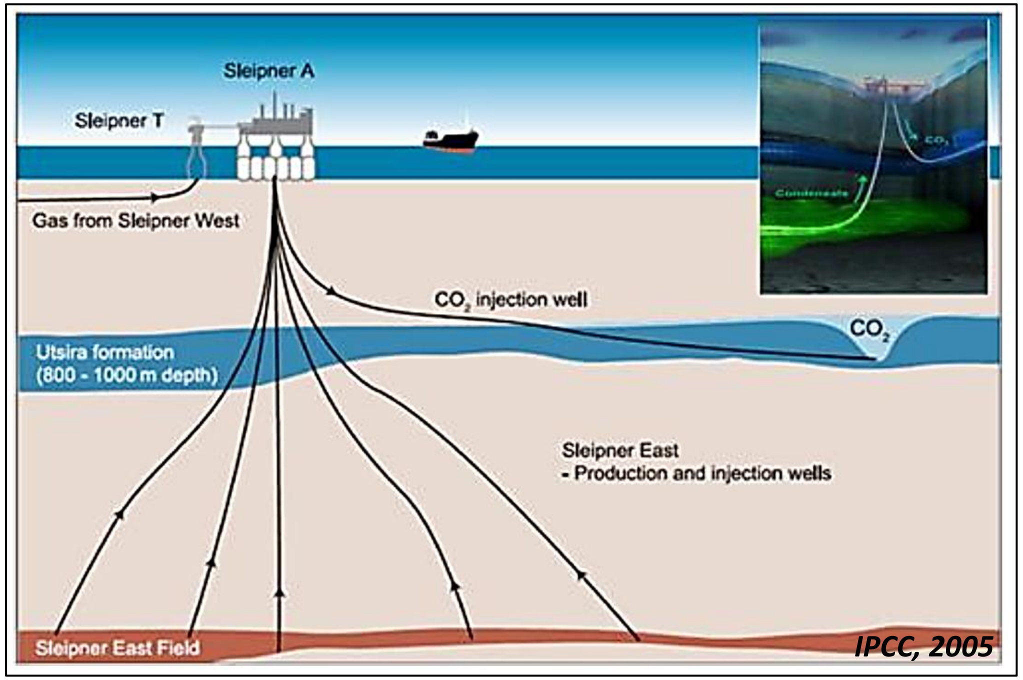


Case study

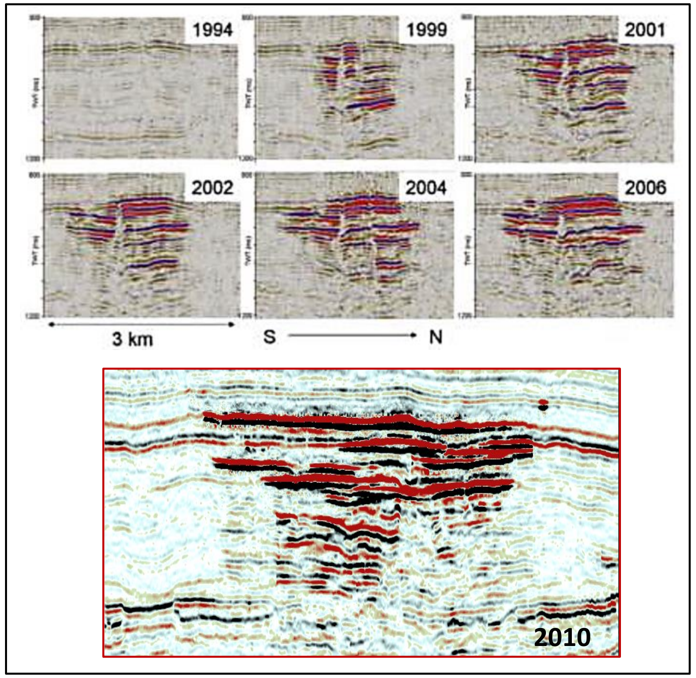
Sleipner Storage Project



Sleipner Field



CO2 Source & Storage

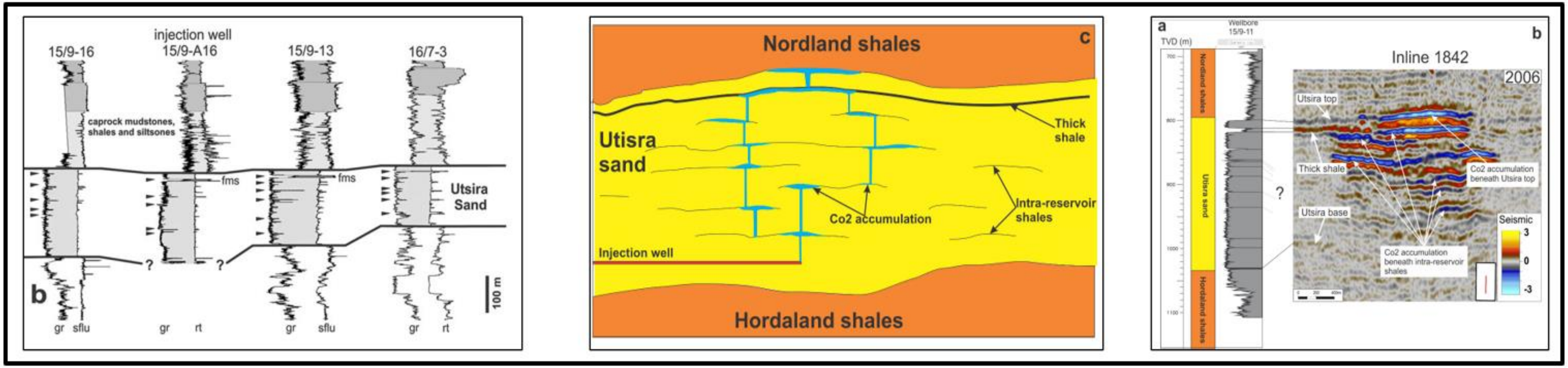


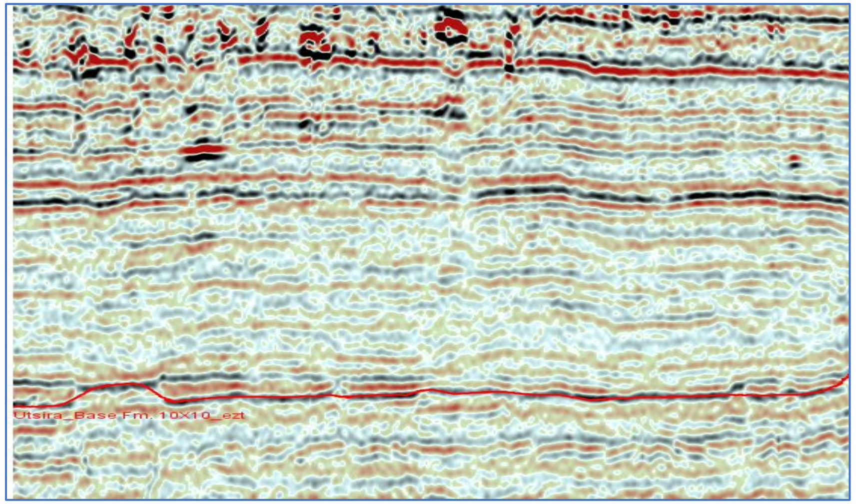
Time-lapse Seismic

- ❑ The world's first industrial-scale CCS project
- ❑ Saline formation of highly porous Utsira Fm. Aquifer was chosen over other storage options
- ❑ More than 24 Mt CO2 injected since 1996 (0.9 MT / year). An amazing real-life laboratory of fluid flow

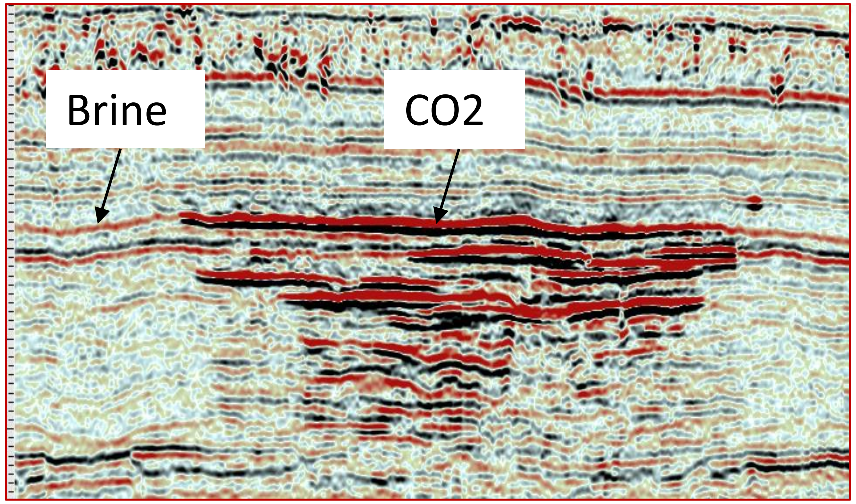
Case study

Sleipner Storage Project





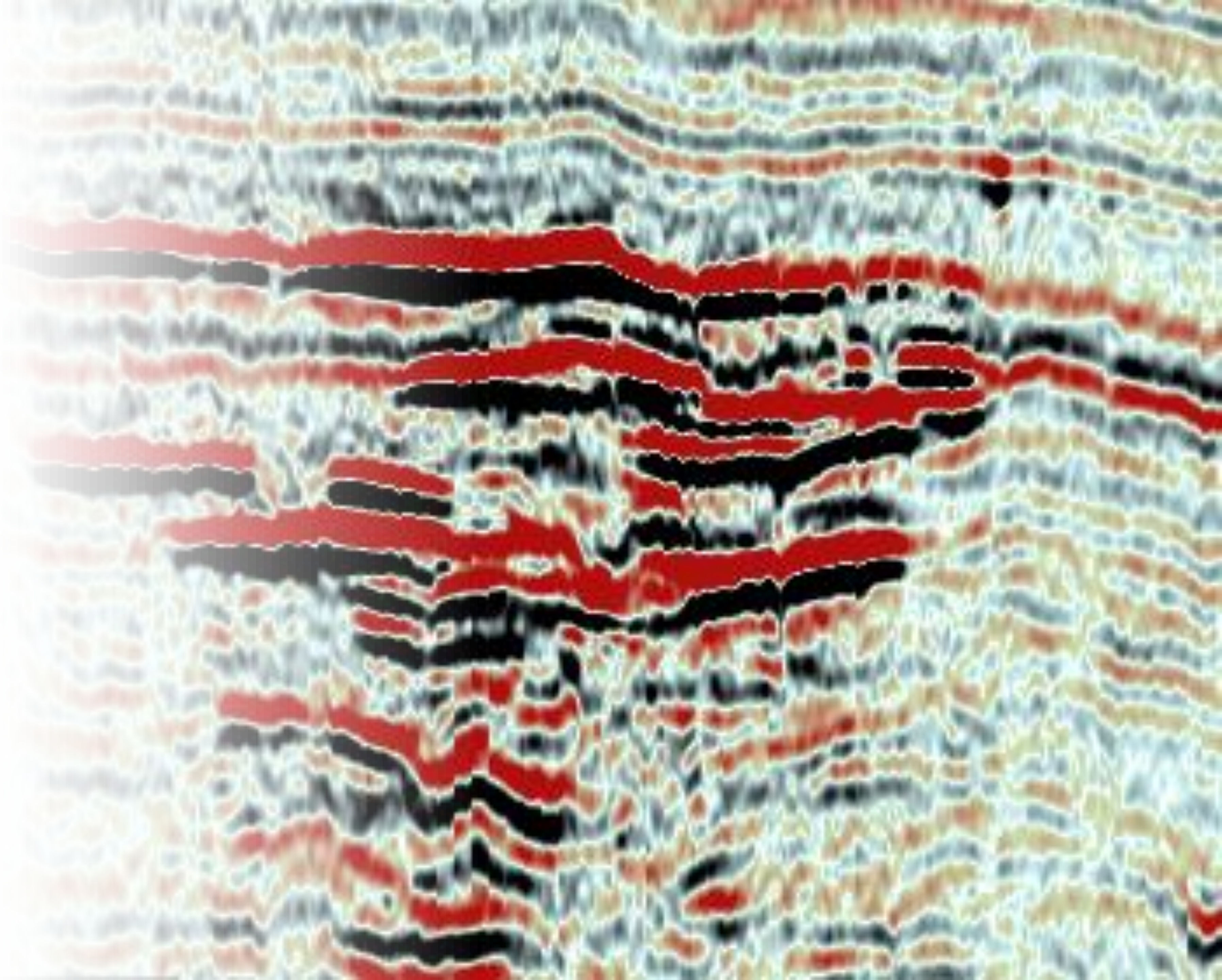
Pre-injection1994



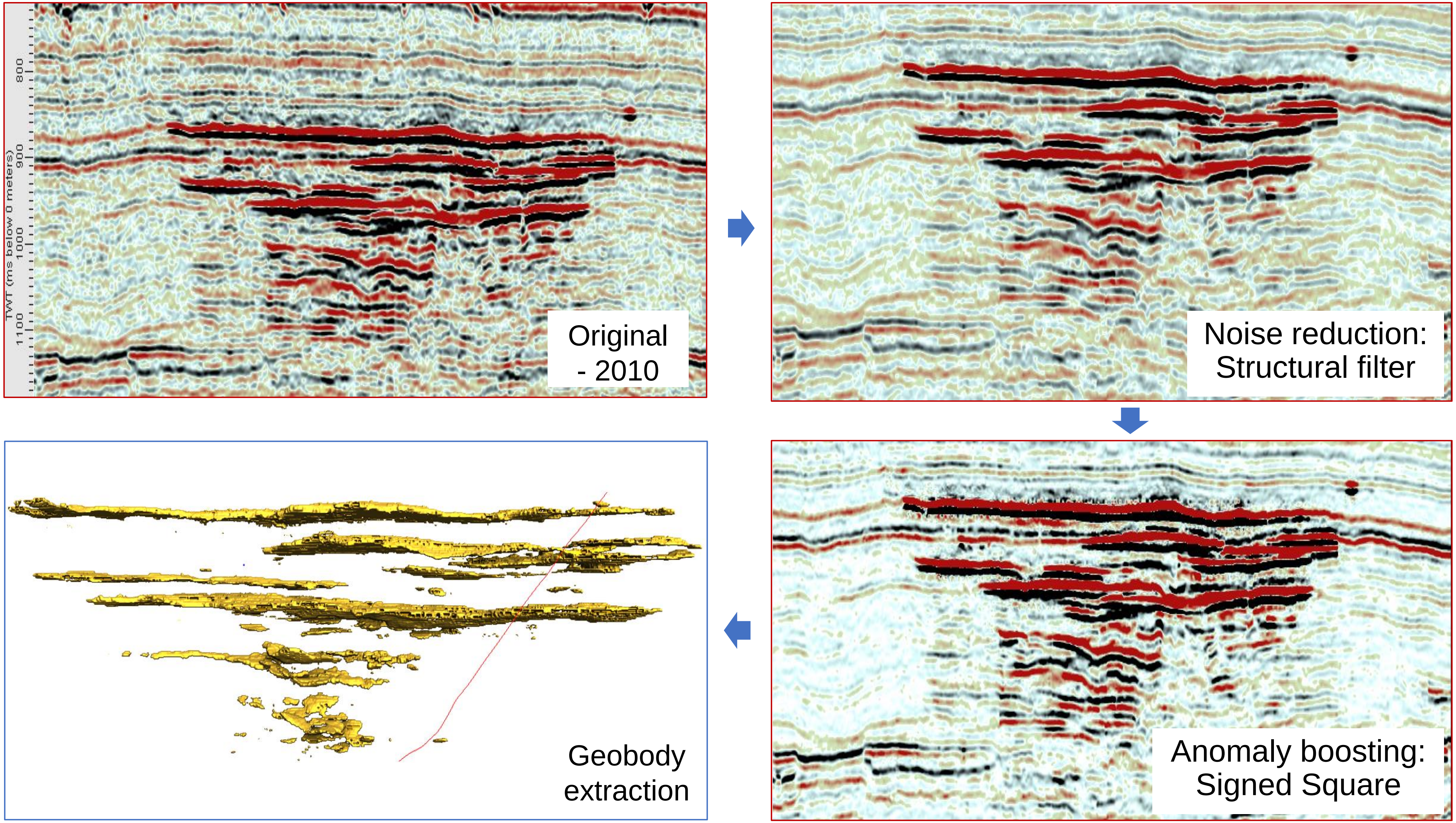
2010

Arts et al. 2008

SEISMIC PLUME ANALYSIS

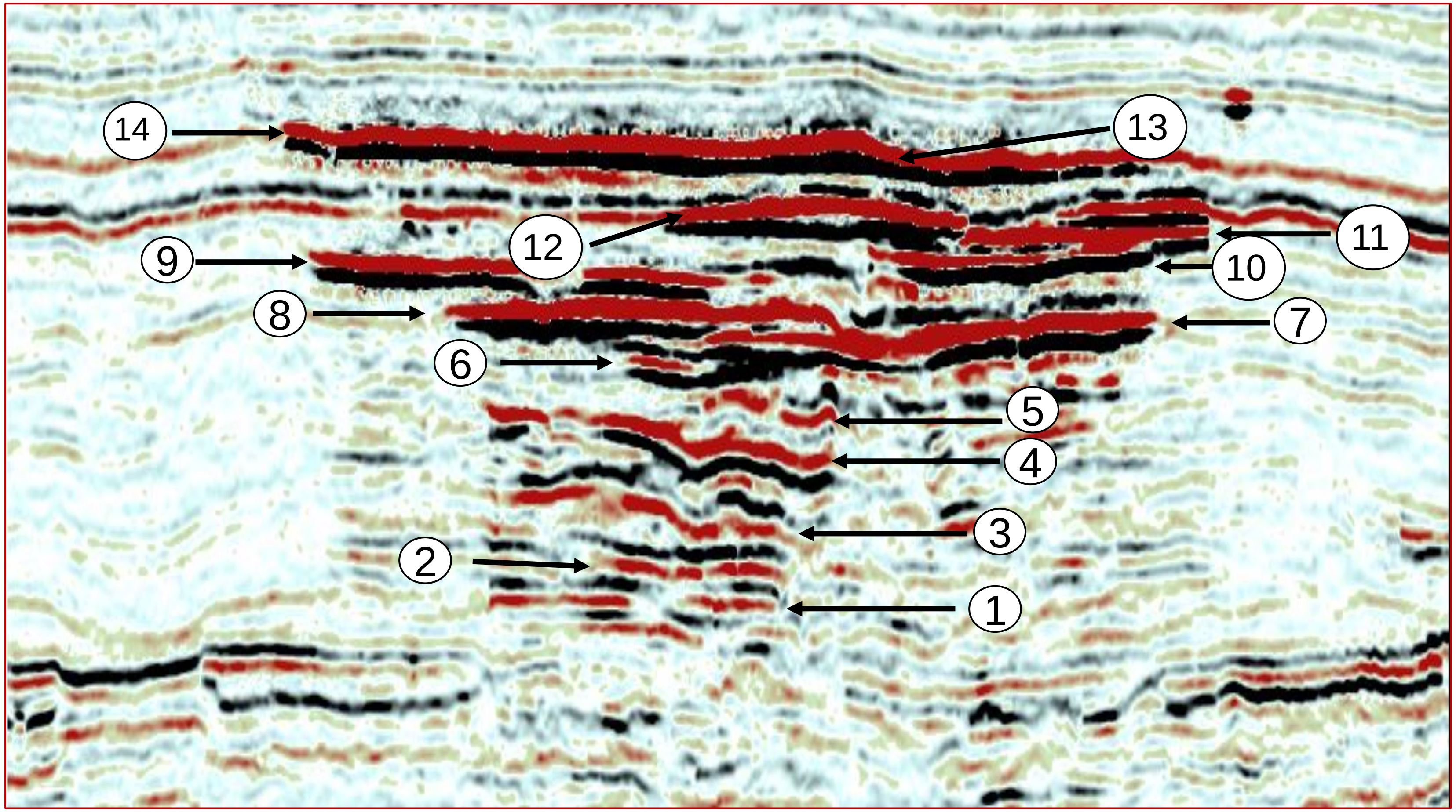


Seismic characterization and insights into the nature of the CO2 plume



Seismic characterization and insights into the nature of the CO_2 plume

- *How many observable layers are actually there?*
- *3 Main sections*



Upper
Dominant structure
Top seal control

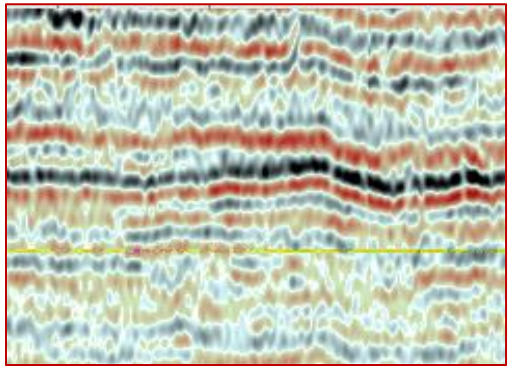
Middle
Strong structural & facies control
Lateral movement

Lower
Strong structural control
Dominant vertical stacking

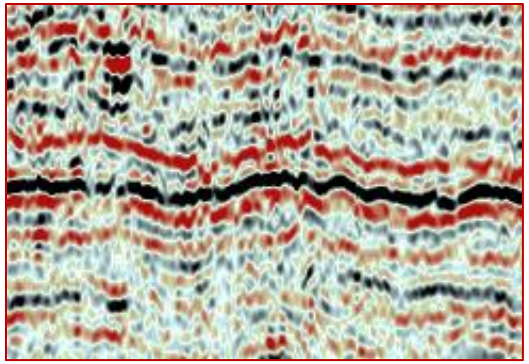
Seismic characterization and insights into the nature of the CO2 plume

1994 processing and attributions to be used for seismic interpretations

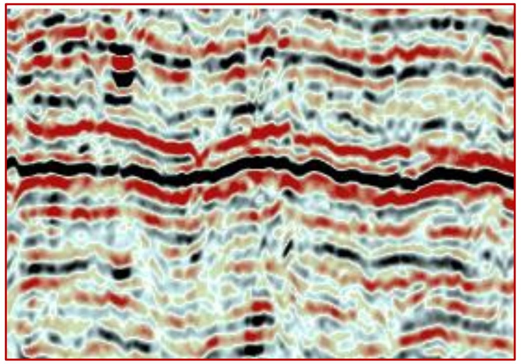
Original



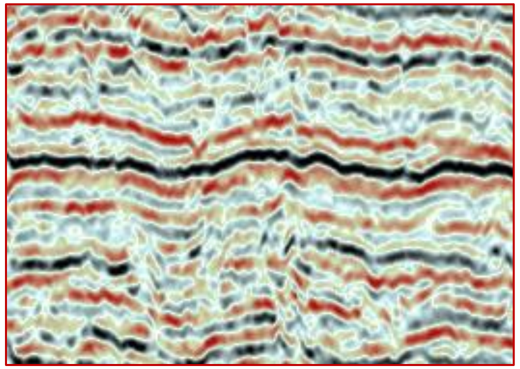
Bandwidth Extension

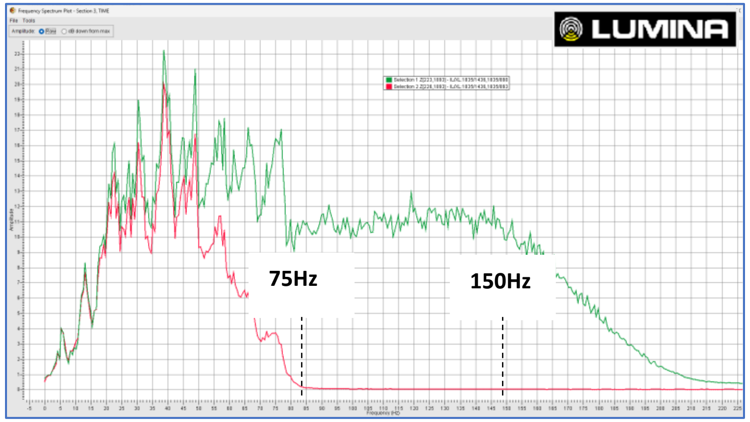


Structural Filter



Envelope Gain



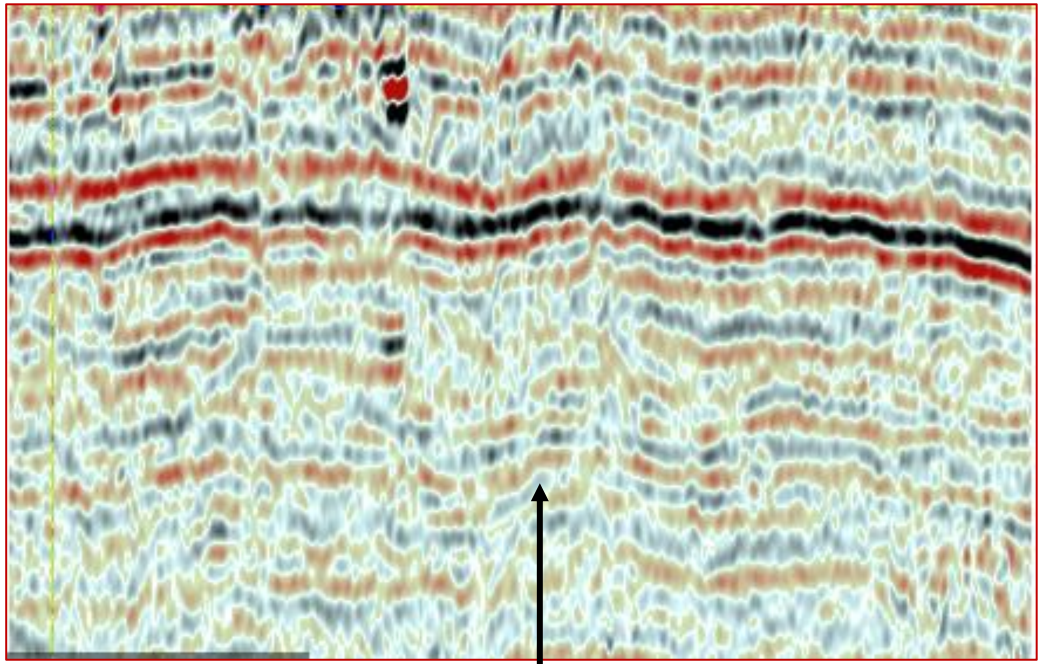


Bandwidth extension using harmonic extrapolation
By LUMINA Geophysics

Seismic characterization and insights into the nature of the CO_2 plume

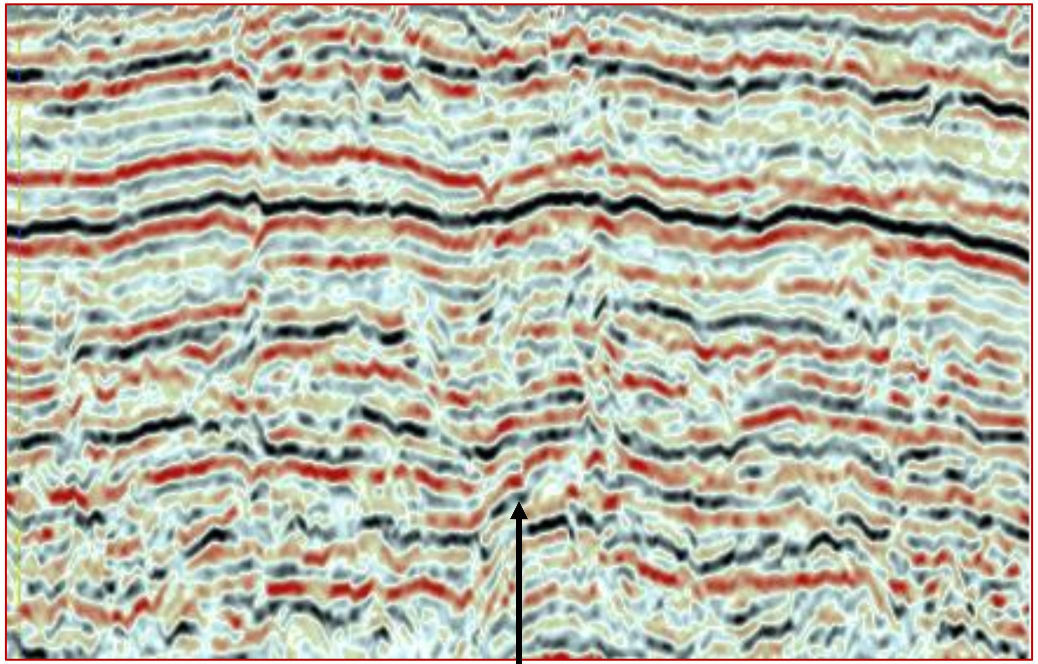
1994: Bandwidth extension, high frequency boosting

Original



- *Low resolution*
- *Attenuated signals*
- *Less continuity*
- *Internal facies architecture unclear*

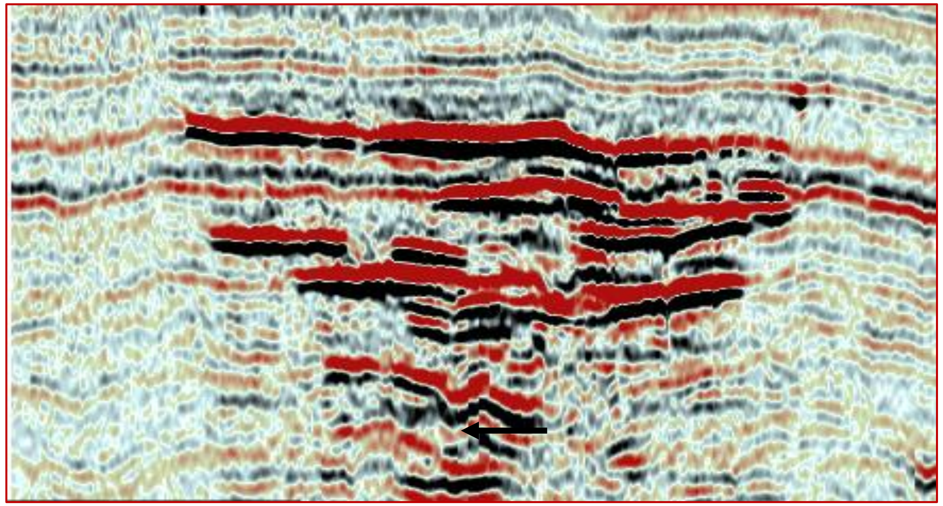
Final processed



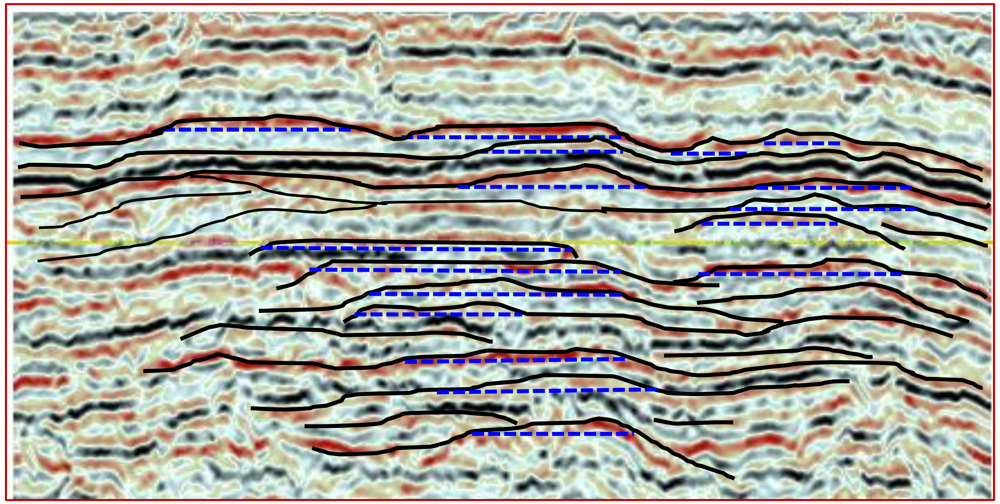
- *Higher resolution*
- *More discernible layers*
- *More continuous*
- *Reveals internal facies architecture*

Seismic facies characterization and insights into the nature of the CO2 plume

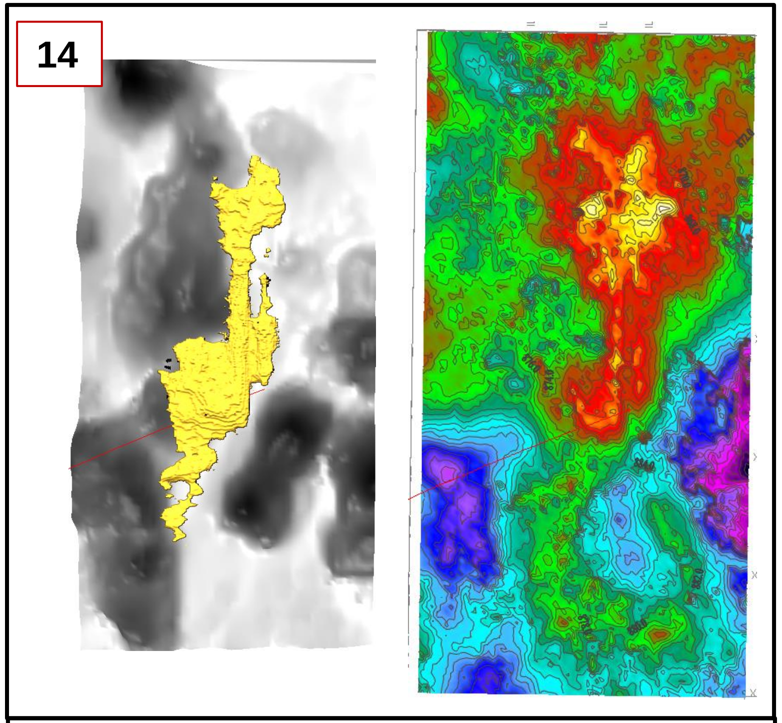
Heterogeneity and the CO2 plume: layer-by-layer analysis

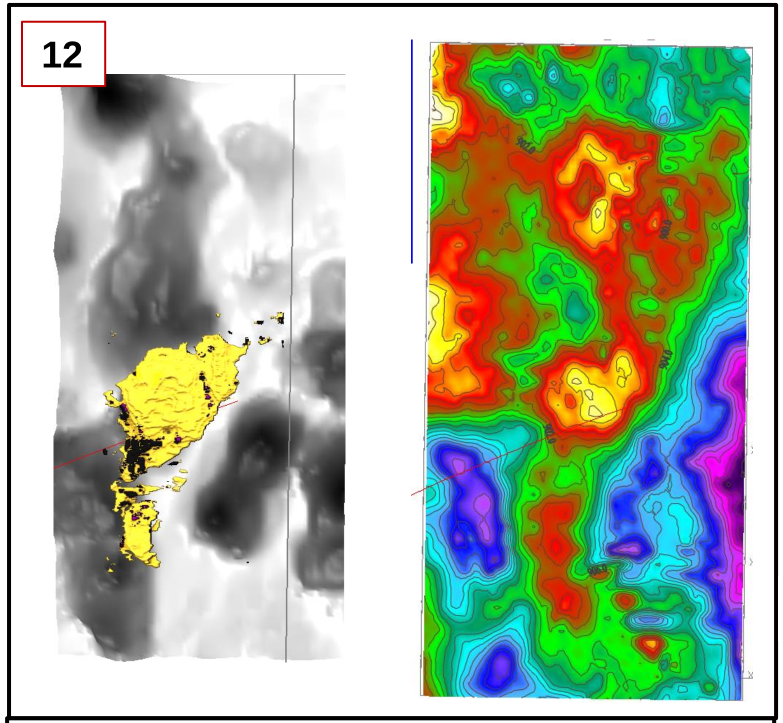


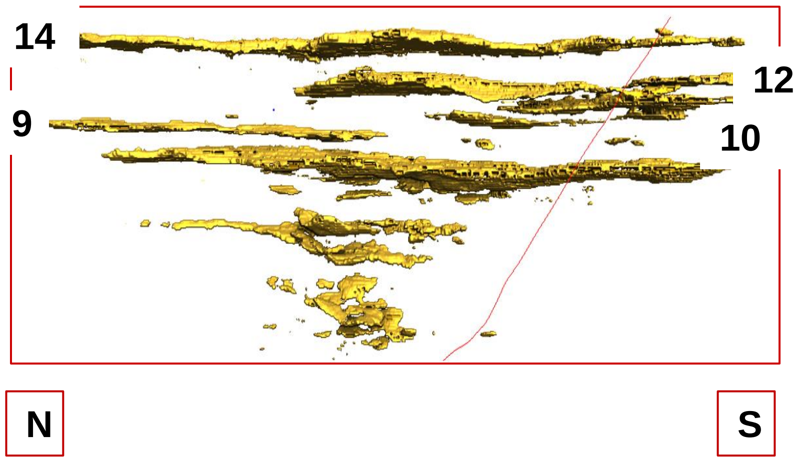
2010
Seismic plume

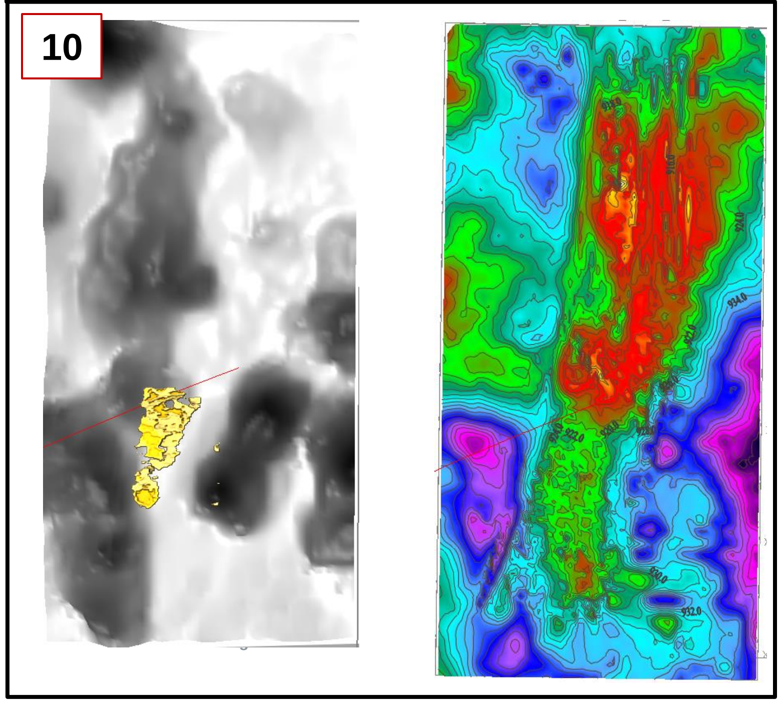


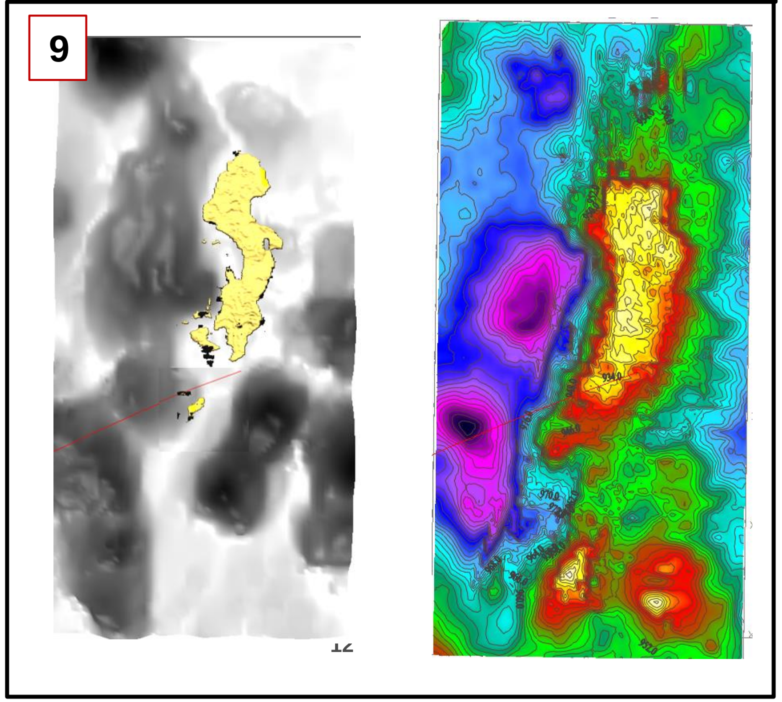
1994
Processed











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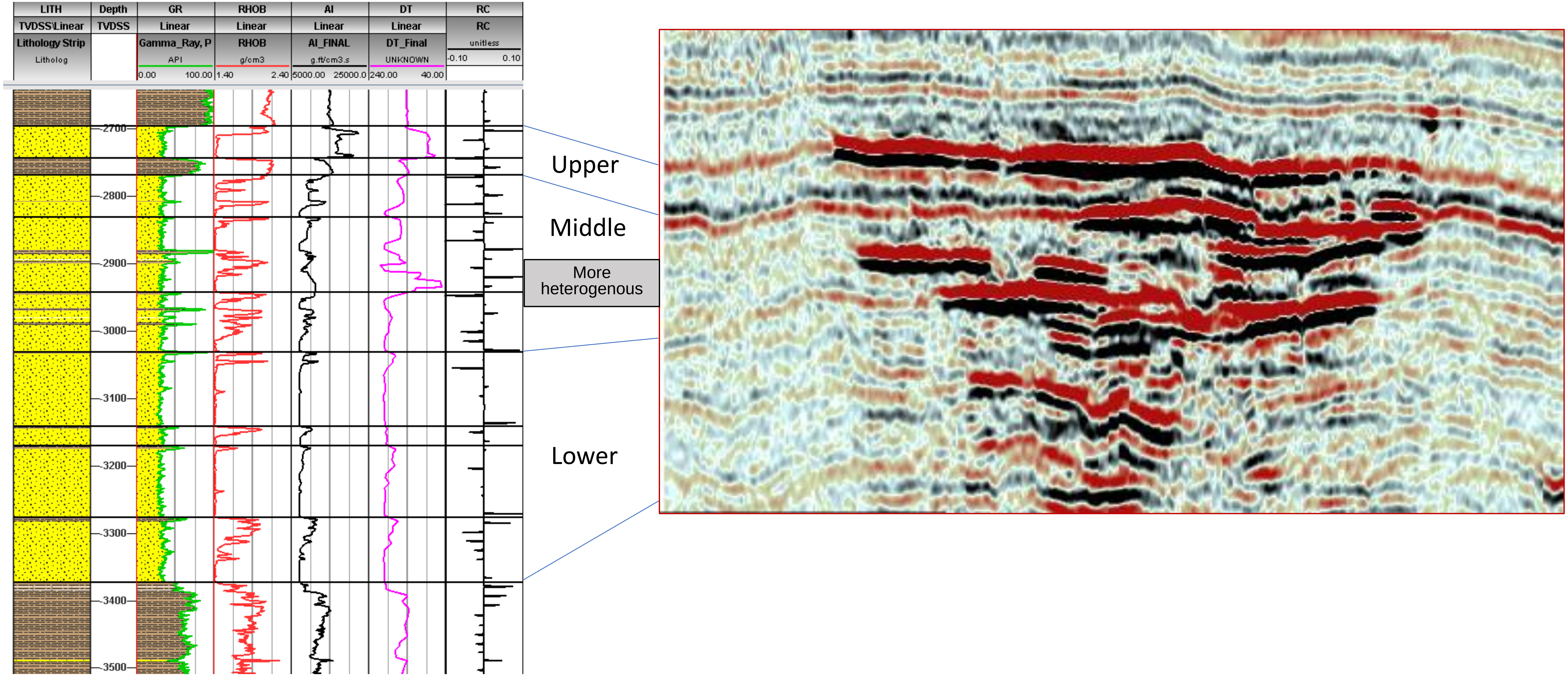
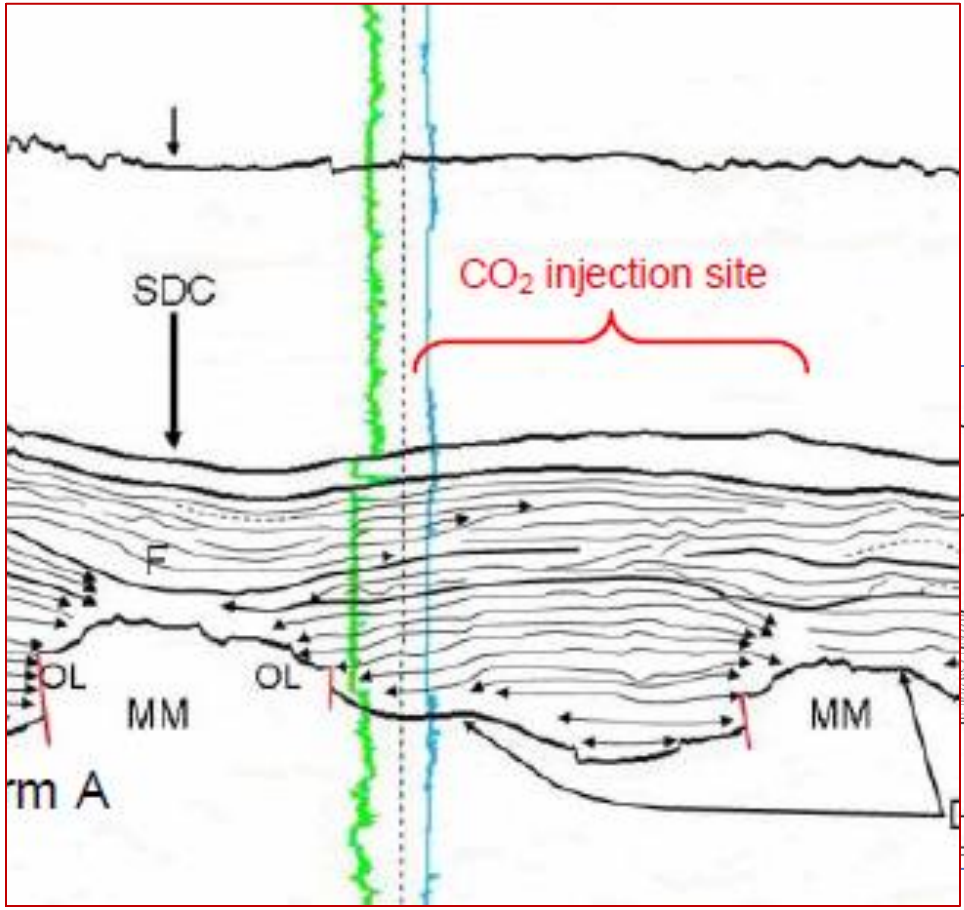
Seismic facies characterization and insights into the nature of the CO2 plume

Well logs

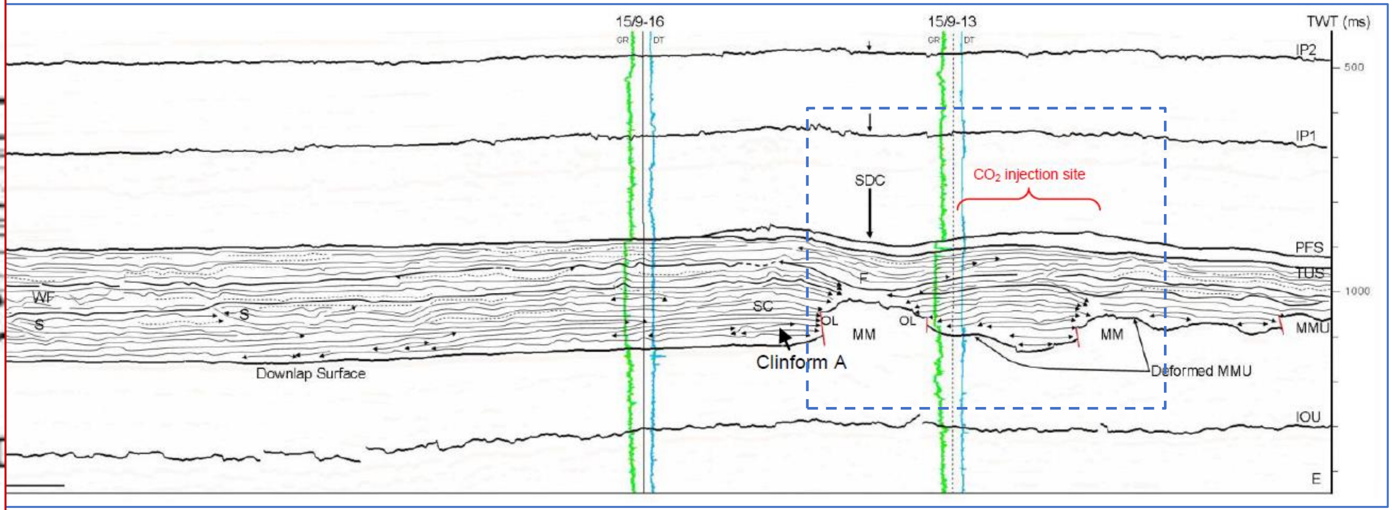


Structural and facies architecture as controlling factors on heterogeneity

Regional Geology Review



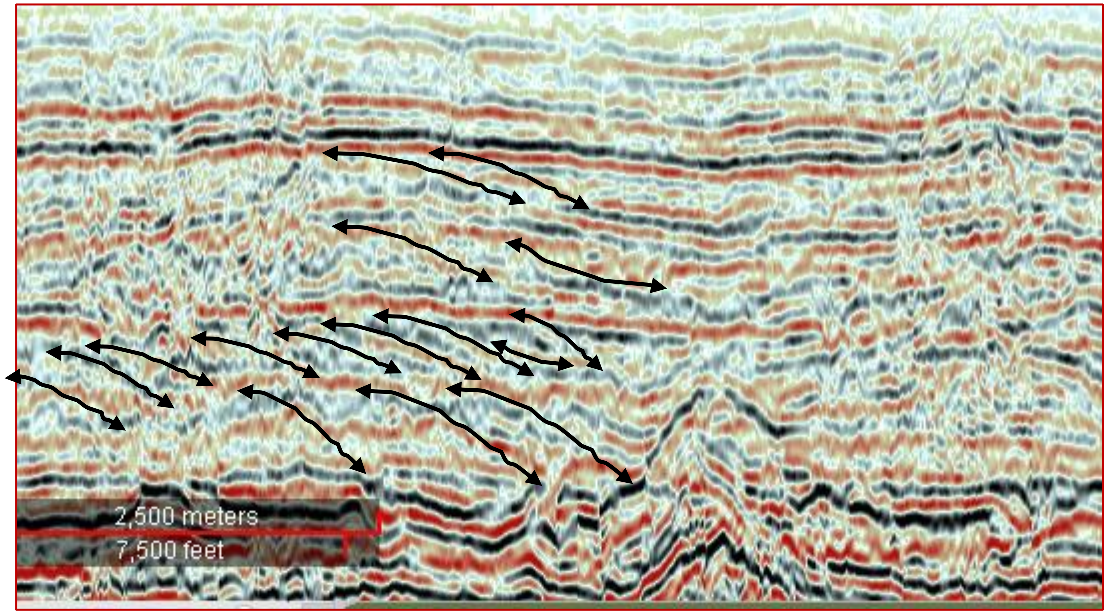
- Seismic reflections within the Utsira fm show complex surface intersections (on-lap, down-lap, top-lap, scouring, and mounds) as the source of stratigraphical heterogeneity. It is consistent with the high-energy nature of marine LST deposition.
- Utsira fm was also deposited syn-structural growth, adding complexity to the depositional process.

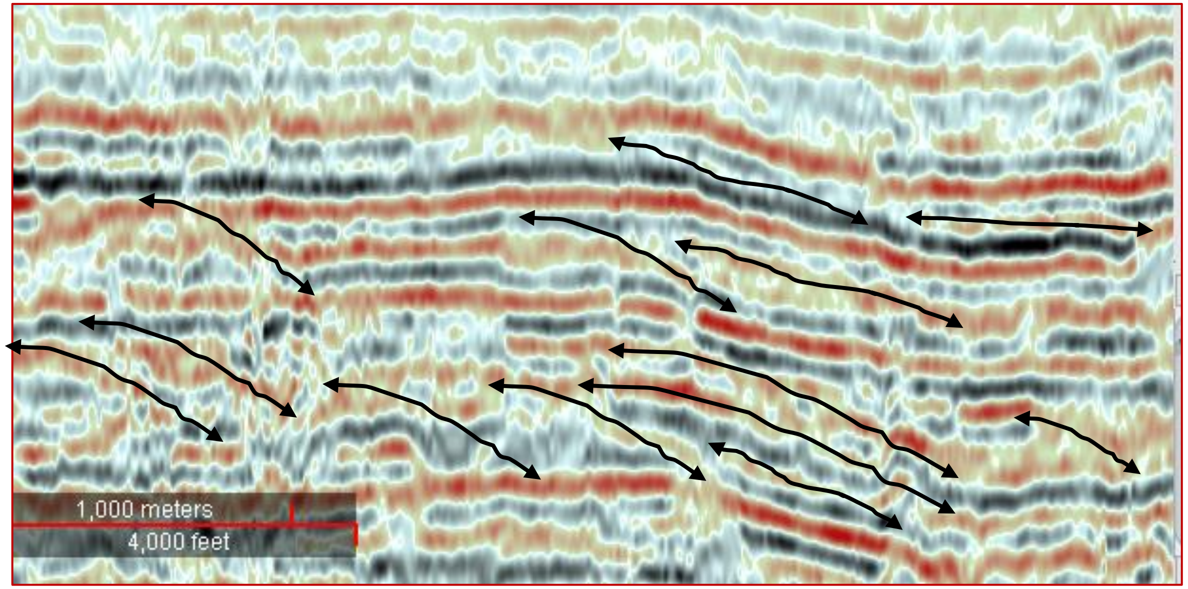


Kennett, Chris., 2008. Evaluation of internal geometries within the Miocene Utsira Formation to establish the geological concept of observed CO2 responses on 4D seismic in the Sleipner area, North Sea. Master Thesis, Imperial College London

Structural and facies architecture as controlling factors on heterogeneity

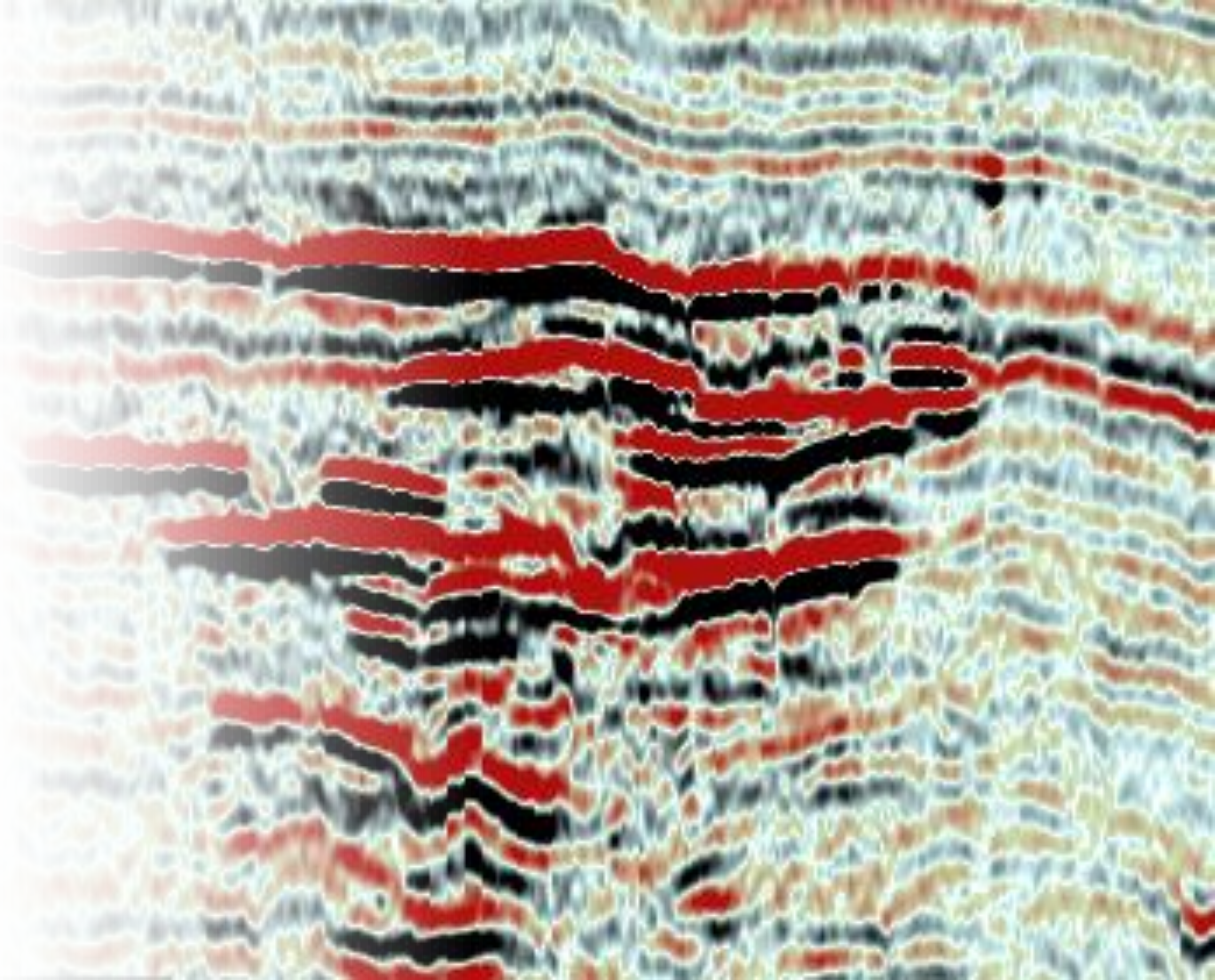
1994 pre-injection seismic





Note: locations and Z section are not disclosed

CO_2 PLUME FLOW DYNAMICS



Why CCS is not like reverse gas engineering

2	CO_2 storage flow physics	More like 'oilfield filling' than hydrocarbon production, and with several additional needs including modelling thermo-elastic responses and geochemical reactions.

Why CCS is not like reverse gas engineering

Philip Ringrose[1,2*], Jamie Andrews[3], Peter Zweigel[1], Anne-Kari Furre[1], Ben Hern[3] and Bamshad Nazarian[1] demonstrate that while many of the tools used for subsurface work are similar, such as seismic surveys and subsurface reservoir modelling, there can be significant differences when applying hydrocarbon subsurface industry experience to CO_2 capture and storage projects.

Introduction

Is geological CO_2 storage essentially the same as hydrocarbon production, only in reverse? It may seem logical to suppose that, since one is 'fluid out' while the other is 'fluid in', it is just a matter of reversing the flow direction. We argue that this is a misguided conclusion on many levels. It is certainly true that many of the tools and methods used for subsurface work are similar, such as drilling technology, petrophysical logging methods, seismic surveys and subsurface reservoir modelling. However, project experience confirms that there can be significant differences that need to be understood when applying hydrocarbon subsurface industry experience to CO_2 capture and storage (CCS) projects.

We summarize these main differences in Table1 and then discuss these differences and similarities below.

Reason 1: CO_2 is not necessarily a gas at subsurface conditions

The first commonly misunderstood difference is that CO_2 does not behave like a gas at subsurface conditions. Below around 800 m depth CO_2 is in a liquid or dense phase. This is not a CO_2 phase we are very familiar with, based on our experience at the Earth's surface. Put simply, dense-phase CO_2 has a gas-like viscosity (around 0.06-0.07 centipoise) but a fluid-like density (500-800 kg/m³). This substance does not behave like methane in

	Distinctive aspect	Summary of key differences
1	Phase behaviour of CO_2	CO_2 is mainly in the liquid or dense phase at subsurface conditions, and phase transitions are very important in transport systems and safety assessments.
2	CO_2 storage flow physics	More like 'oilfield filling' than hydrocarbon production, and with several additional needs including modelling thermo-elastic responses and geochemical reactions.
3	Data support	Storage site assessment and forecasting is typically done with fewer wells and less available seismic data than for typical hydrocarbon field developments.
4	Longer forecasting timescales	CO_2 storage projects need to assess the injection period, the post injection period, and the longer-term processes for hundreds of years into the future.
5	Well design	Preferred well placement, metal components needed for corrosion control and cementation and well isolation procedures are significantly different from standard oil and gas fields.
6	Storage integrity assurance	Site integrity evaluation requires substantially more effort and detail than is typically the case for oil and gas fields.
7	The socio-economic discourse	CCS projects are socially very different from O&G projects: They address climate goals, contribute to new infrastructure investments, rely on green-financing models, and need significant efforts to address public concerns about safety and the environment.

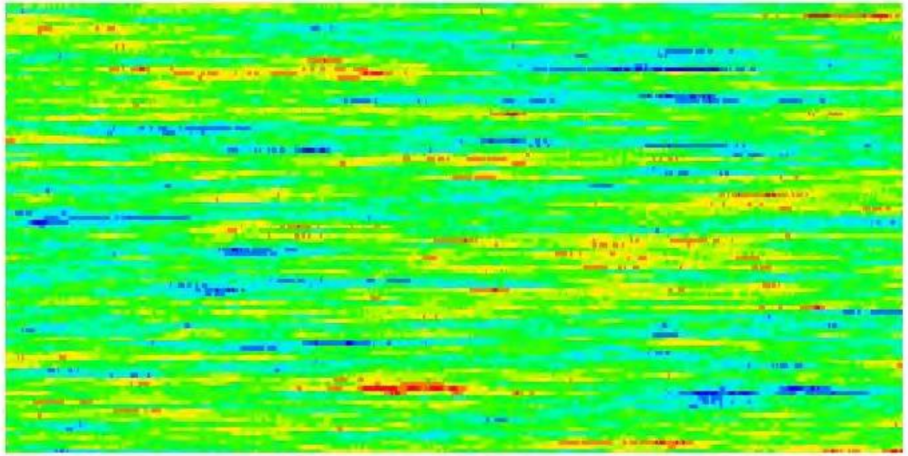
Table 1 Summary of the main distinctive aspects of CCS projects outlined in this review.

[1] Equinor ASA Trondheim | [2] NTNU, Trondheim | [3] Equinor ASA Stavanger
[*] Corresponding author, E-mail: phiri@equinor.com
DOI: 10.3997/1365-2397.fb2022088

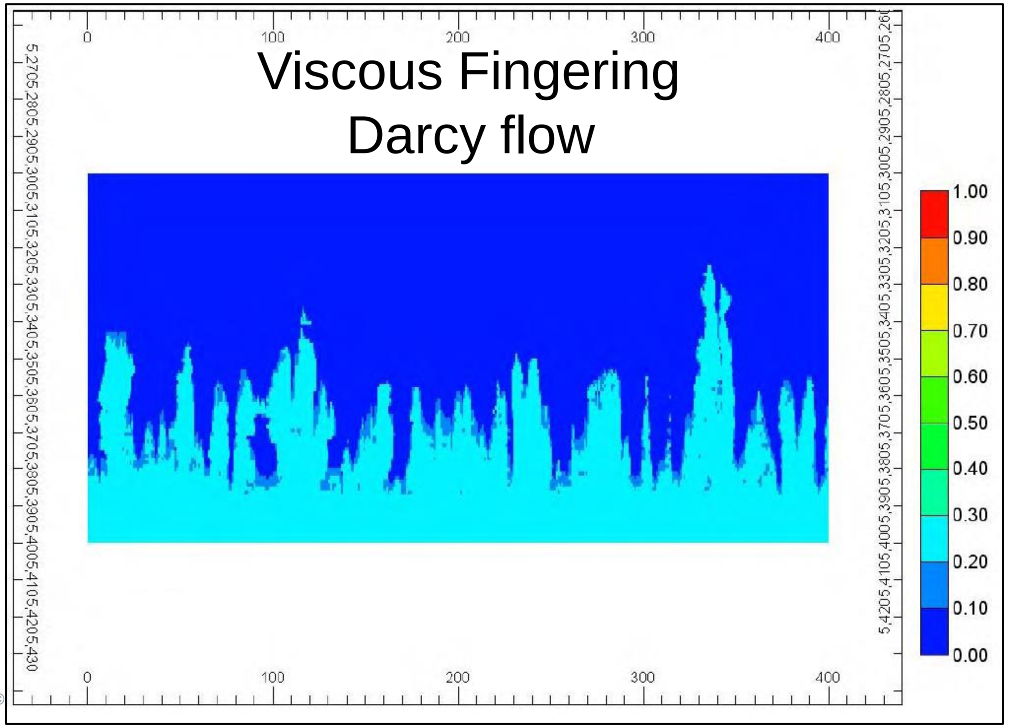
FIRST BREAK by EAGE, 2022

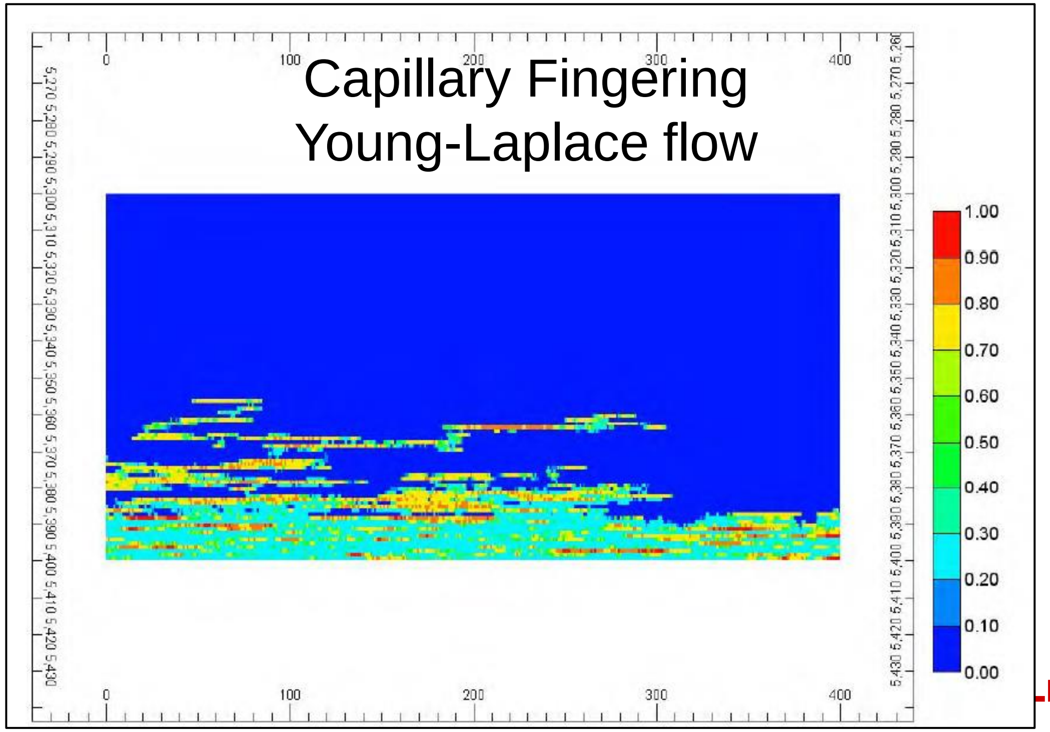
Simulation Experiments

Saadatpoor et al (2007)

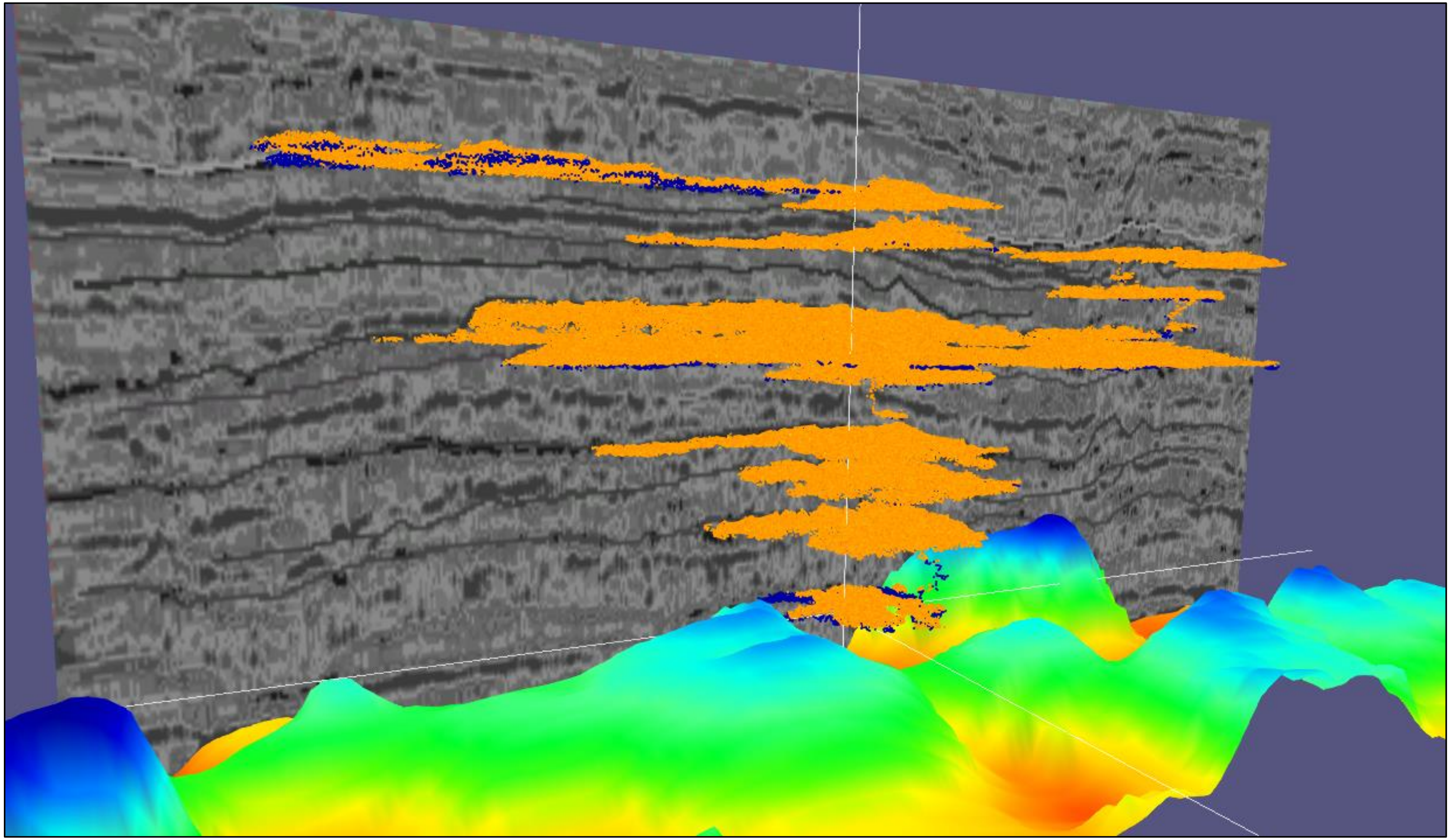


Base model



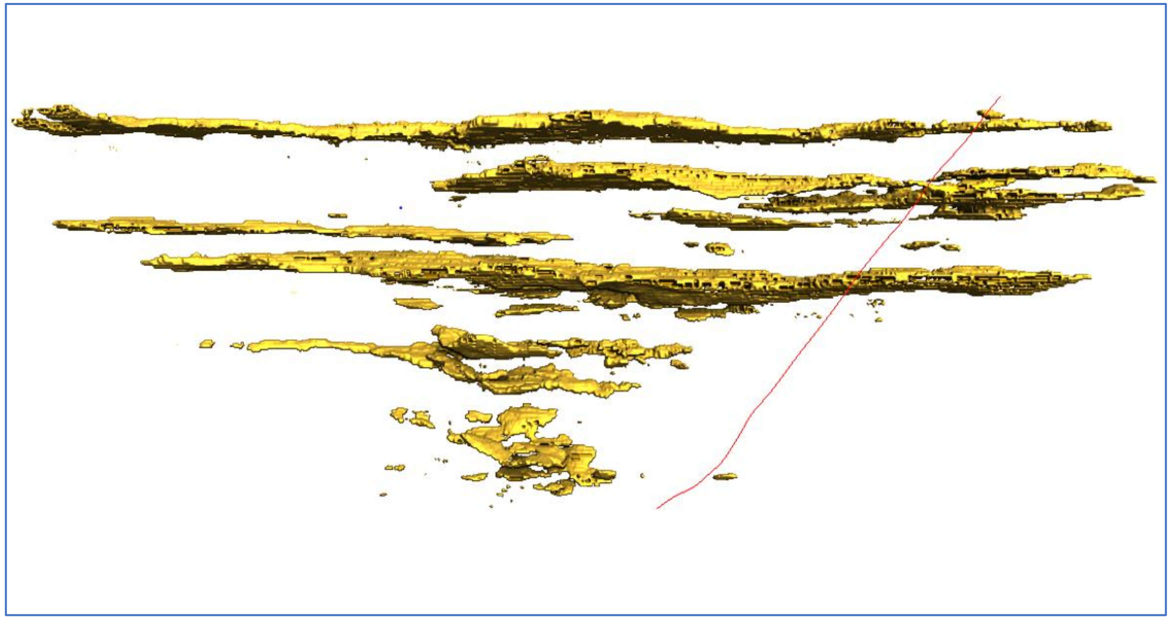


Young-Laplace Flow – Invasion percolation model

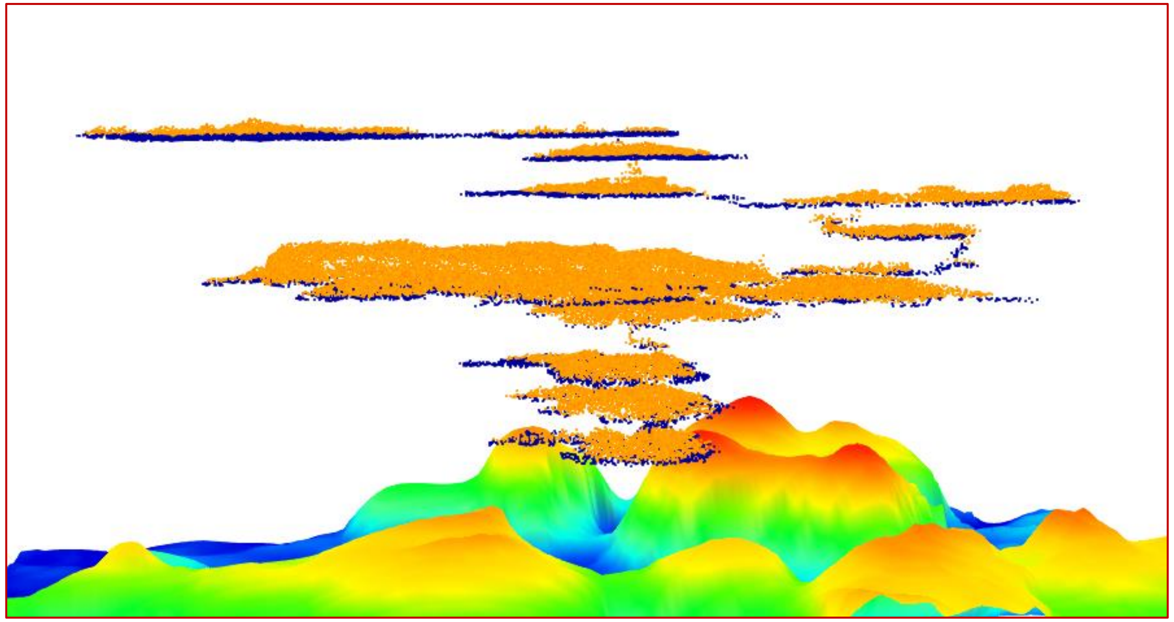


Plume shapes comparison

Geobodies from Seismic plume 2010 (3D view)



Young-Laplace Simulation Model (3D view)

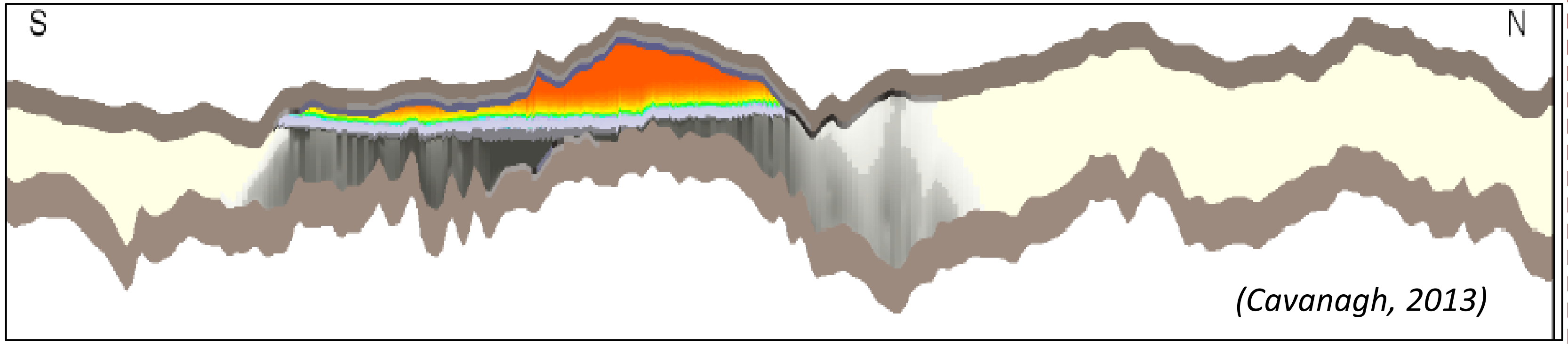


CO_2 Plume VS Pressure Plume

Simulations at the Top layer

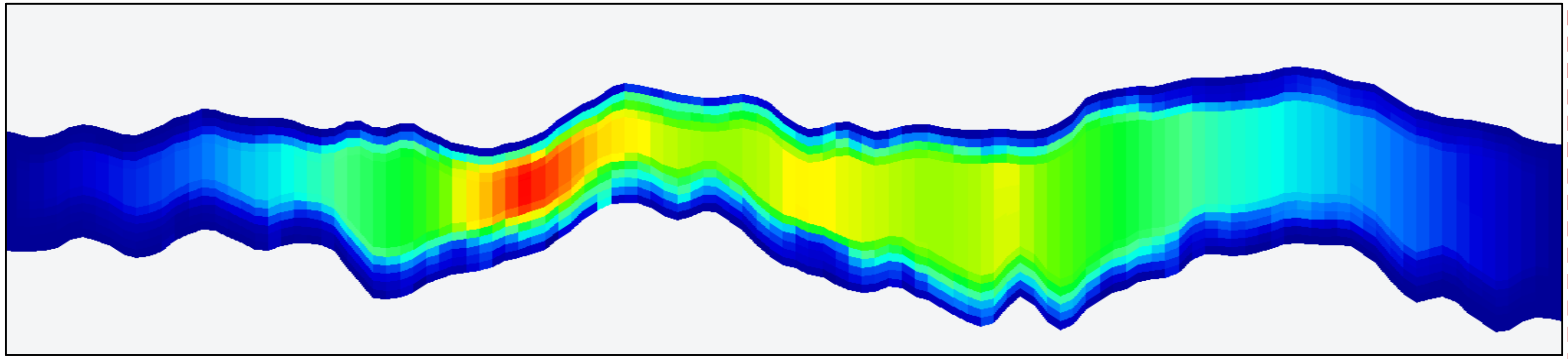
Governing physics

CO2
(Multi-phase fluid)



Young-Laplace

Pressure/Brine
(single-phase fluid)



Darcy
(Single phase)

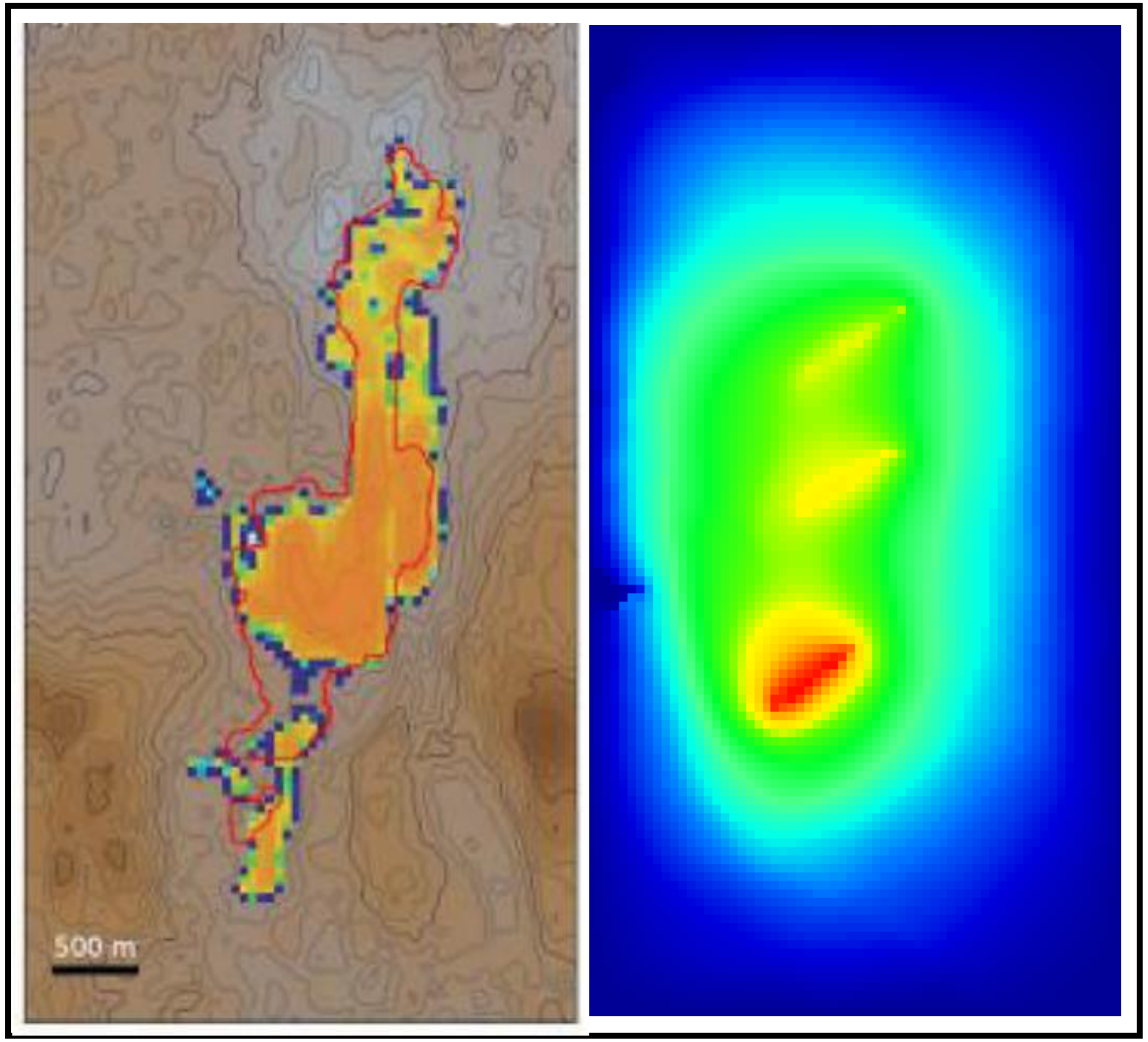
*While $CO2$ sequestration is a multi-phase fluid flow problem at the reservoir scale, **the single-phase fluid controls the far-field pressure response** and brine flow (Birkholzer. et al, 2015, Amirlatifi et al, 2022).*

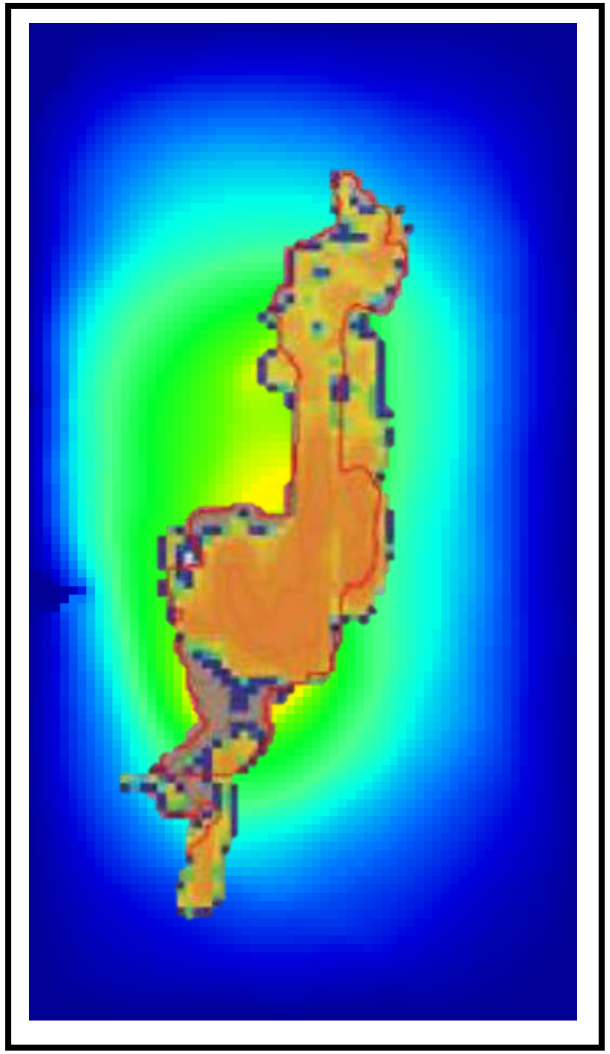
***Shales** are effectively perfect seals with respect to CO2 flow, but **open with respect to single-phase flow**, allowing natural pressure dissipation out of the storage formation (IEAGHG, 2010).*

CO2 Plume VS Pressure Plume

Simulations at the Top layer

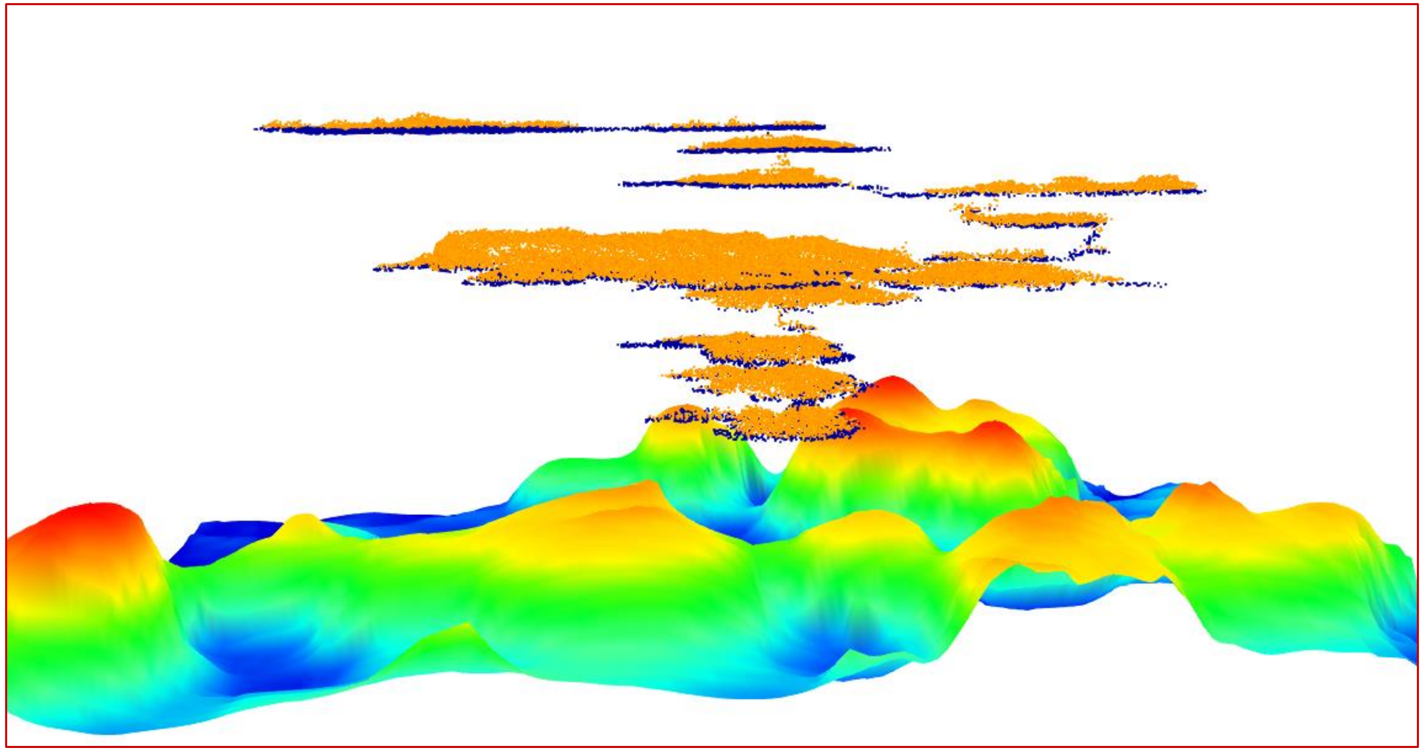
CO2 **Pressure/Brine**





Summary

- Bandwidth extension + attributions to improve the imaging of seismic heterogeneity
- Small-scale heterogeneity (facies architecture) strongly controls plume anatomy
- CO_2 flow physics: capillary-gravity driven (Young-Laplace Flow)
- Pressure perturbation: single-phase darcy flow



THANK YOU

JOGMEC
Japan Oil, Gas and Metals National Corporation

equinor

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LUMINA

SPE International
Aberdeen Section